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New QCD Sum Rules for Nucleons in Nuclear Matter

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Abstract

Two new QCD sum rules for nucleons in nuclear matter are obtained from a mixed correlator of spin-1/2 and spin-3/2 interpolating fields. These new sum rules, which are insensitive to the poorly known four-quark condensates, provide additional information on the nucleon scalar self-energy. These new sum rules are analyzed along with previous spin-1/2 interpolator-based sum rules which are also insensitive to the poorly known four-quark condensates. The analysis indicates consistency with the expectations of relativistic nuclear phenomenology at nuclear matter saturation density. However, a weaker density dependence near saturation is suggested. Using previous estimates of in-medium condensate uncertainties, we find $M^* = 0.64^{+0.13}_{-0.09}$ GeV and $\Sigma_v = 0.29^{+0.06}_{-0.10}$ GeV at nuclear matter saturation density.

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Understanding the observed properties of hadrons and nuclei from quantum chromodynamics (QCD) is a principal goal of nuclear theorists. The QCD sum-rule approach [1] is a particularly useful method for connecting the properties of QCD to observed nuclear phenomena [2–10]. Recent progress in understanding the origin of the large and canceling isoscalar Lorentz-scalar and -vector self-energies for propagating nucleons in nuclear matter has been made via the analysis of QCD sum rules generalized to finite nucleon density [2–6]. These large self-energies are central to the success of relativistic nuclear phenomenology [11].

However, the previous sum-rule predictions for the scalar self-energy are sensitive to the density dependence of chirally-even dimension-six four-quark condensates. In-medium factorization expresses these chirally-even operators in terms of the square of a chirally-odd operator whose density dependence is likely to be very different. As such, the density dependence of these problematic four-quark operators is generally unknown [3,5,6].

There are various ways to clarify the situation. One approach attempts to better determine the density dependence of the four-quark condensates via modeling [12]. One may also use other independent information to constrain the in-medium four-quark condensates [13]. An alternative approach, which is adopted here, is to derive new QCD sum rules that are insensitive to the four-quark condensates.

In this work, we obtain two new sum rules from a mixed correlator of generalized spin–1/2 and spin–3/2 interpolating fields. The spin–1/2 states remain projected, and one generates additional sum rules for the nucleon scalar self-energy that are insensitive to the four-quark condensates. Our hope is that these new sum rules, along with previous spin–1/2 interpolator-based sum rules which are insensitive to the problematic four-quark condensates [3,5,6], will allow a better determination of the nucleon self-energies in nuclear matter.

The finite-density QCD sum-rule approach focuses on a correlation function of interpolating fields carrying the quantum numbers of the hadron of interest. The correlation function is evaluated in the ground state of nuclear matter instead of the QCD vacuum. The appearance of an additional four-vector at finite density, the four-velocity of the nuclear medium, leads to additional invariant functions relative to the vacuum case [2–6,14]. In the rest frame of the medium, the analytic properties of the various invariant functions can be studied through Lehman representations in energy. The quasi-nucleon excitations (i.e., the quasiparticle excitations with nucleon quantum numbers) are characterized by the discontinuities of the invariant functions across the real axis, which are used to identify the on-shell self-energies. A representation of the correlation function can be obtained by introducing a simple phenomenological Ansatz for these spectral densities.

On the other hand, the correlation function can be evaluated at large space-like momenta using an operator product expansion (OPE). This expansion requires knowledge of QCD Lagrangian parameters and finite-density quark and gluon matrix elements (condensates). Finite-density QCD sum rules, which relate the nucleon self-energies in the nuclear medium to these QCD inputs, are obtained by equating the two different representations using appropriately weighted integrals [3,5,6].

Consider the correlation function defined by

$$\Pi^{12}_{\mu\nu}(q) \equiv i \int d^4x \, e^{iq\cdot x} \langle \Psi_0 | T \left[\chi^1_\mu(x) \, \overline{\chi}^2_\nu(0) \right] | \Psi_0 \rangle \, , \tag{1}$$

where the ground state of nuclear matter $|\Psi_0\rangle$ is characterized by the rest-frame nucleon

density ρ_N and by the four-velocity u^μ; it is assumed to be invariant under parity and time reversal except for the transformation of u^μ. The interpolating fields are taken to be [15,16]

$$\chi^1_\mu(x) = \gamma_\mu \gamma_5 \epsilon^{abc} \left\{ \left[u^T_a(x)\, C\, \gamma_5\, d_b(x) \right] u_c + \beta \left[u^T_a(x)\, C\, d_b(x) \right] \gamma_5\, u_c(x) \right\} , \tag{2}$$

$$\chi^2_\nu(x) = \epsilon^{abc} \left\{ \left[u^T_a(x)\, C\, \sigma_{\rho\lambda}\, d_b(x) \right] \sigma^{\rho\lambda}\, \gamma_\nu\, u_c(x) - \left[u^T_a(x)\, C\, \sigma_{\rho\lambda}\, u_b(x) \right] \sigma^{\rho\lambda}\, \gamma_\nu\, d_c(x) \right\} , \tag{3}$$

where T denotes a transpose in Dirac space, C is the charge conjugation matrix, and β is a parameter allowing for arbitrary mixing of the two independent spin-1/2 interpolating fields [17].

The correlator of χ^1_μ and $\overline{\chi}^1_\nu$ gives the sum rules discussed extensively in Refs. [2–6]. In particular, the sum rule at the structure, $\gamma_\mu \not{u} \gamma_\nu$, strongly depends on the even-chirality four-quark condensates, $\langle \overline{q}\, \Gamma_i\, q\, \overline{q}\, \Gamma_i\, q \rangle_{\rho_N}$ and $\langle \overline{q}\, \Gamma_i\, \lambda_a\, q\, \overline{q}\, \Gamma_i\, \lambda_a\, q \rangle_{\rho_N}$, where λ^a are the Gell-Mann matrices and Γ_i are any of the 16 Dirac matrices. The other two sum rules are insensitive to these even-chirality four-quark condensates and are given by

$$\begin{aligned}
\lambda_1^2\, M_N^*\, e^{-(E_q^2 - \mathbf{q}^2)/M^2} &= -\frac{7 - 2\beta - 5\beta^2}{64\pi^2}\, M^4\, E_1\, \langle \overline{q} q \rangle_{\rho_N} \\
&\quad + \frac{3\,(1-\beta^2)}{64\pi^2}\, M^2\, E_0\, \langle g_c \overline{q}\, \sigma\!\cdot\!\mathcal{G} q\, \rangle_{\rho_N}\, L^{-14/27} \\
&\quad - \frac{7 - 2\beta - 5\beta^2}{12}\, \overline{E}_q\, \langle \overline{q} q \rangle_{\rho_N}\, \langle q^\dagger q \rangle_{\rho_N} \\
&\quad - \frac{9 + 10\beta - 29\beta^2}{2^7\, 3^2}\, \langle \overline{q} q \rangle_{\rho_N}\, \langle \frac{\alpha_s}{\pi} G^2 \rangle_{\rho_N} ,
\end{aligned} \tag{4}$$

and

$$\begin{aligned}
\lambda_1^2\, \Sigma_v\, e^{-(E_q^2 - \mathbf{q}^2)/M^2} &= \frac{5 + 2\beta + 5\beta^2}{48\pi^2}\, M^4\, E_1\, \langle q^\dagger q \rangle_{\rho_N}\, L^{-4/9} \\
&\quad + \frac{5\,(5 + 2\beta + 5\beta^2)}{72\pi^2}\, \overline{E}_q\, M^2\, E_0\, \langle q^\dagger i D_0 q \rangle_{\rho_N}\, L^{-4/9} \\
&\quad - \frac{7 + 10\beta + 7\beta^2}{192\pi^2}\, M^2\, E_0\, \langle g_c q^\dagger \sigma\!\cdot\!\mathcal{G} q \rangle_{\rho_N}\, L^{-4/9} \\
&\quad + \frac{5 + 2\beta + 5\beta^2}{8\pi^2}\, \mathbf{q}^2 \left(\langle q^\dagger i D_0 i D_0 q \rangle_{\rho_N} + \frac{1}{12} \langle g_c q^\dagger \sigma\!\cdot\!\mathcal{G} q \rangle_{\rho_N} \right) L^{-4/9} \\
&\quad + \frac{5 + 2\beta + 5\beta^2}{12}\, \overline{E}_q\, \kappa\, \langle q^\dagger q \rangle^2_{\rho_N}\, L^{-4/9} .
\end{aligned} \tag{5}$$

Here λ_1 denotes the coupling of χ^1_μ to the quasi-nucleon state. We have also defined

$$M_N^* \equiv M_N + \Sigma_s , \qquad E_q \equiv \Sigma_v + \sqrt{\mathbf{q}^2 + M_N^{*2}} , \qquad \overline{E}_q \equiv \Sigma_v - \sqrt{\mathbf{q}^2 + M_N^{*2}} , \tag{6}$$

where Σ_s and Σ_v are the scalar and vector self-energies of the nucleon in nuclear matter, respectively. The anomalous dimensions of various operators have been taken into account through the factor $L \equiv \ln(M^2/\Lambda^2_{\rm QCD})/\ln(\mu^2/\Lambda^2_{\rm QCD})$ [1]. We have also defined $E_0 \equiv 1 - e^{-s_0/M^2}$ and $E_1 \equiv 1 - e^{-s_0/M^2}\,(s_0/M^2 + 1)$, which account for excited-state contributions [3,5,6,18].

In sum rules (4) and (5), contributions proportional to the up and down current quark masses have been neglected as they give numerically small contributions. The contributions of the even-chirality four-quark condensates to the sum rule (4) are proportional to current quark masses and can thus be neglected safely. Their contributions to (5) appear only in the form of $\langle\overline{q}\,\gamma_0\,q\,\overline{q}\,\gamma_0\,q\rangle_{\rho_N} - \frac{1}{4}\langle\overline{q}\,\gamma^\mu\,q\,\overline{q}\,\gamma_\mu\,q\rangle_{\rho_N}$ or $\langle\overline{q}\,\gamma_0\,\lambda_a\,q\,\overline{q}\,\gamma_0\,\lambda_a\,q\rangle_{\rho_N} - \frac{1}{4}\langle\overline{q}\,\gamma^\mu\,\lambda_a\,q\,\overline{q}\,\gamma_\mu\,\lambda_a\,q\rangle_{\rho_N}$. It is easy to see that these two combinations go to zero in the zero density limit and they are proportional to ρ_N in the linear density approximation. Here we will assume in-medium factorization for these *combinations*. To explore the sensitivity of this assumption, we have introduced the parameter κ in (5) such that deviations from in-medium factorization ($\kappa = 1$) may be explored during the Monte-Carlo based uncertainty analysis. The remaining nonvanishing four-quark condensates, $\langle\overline{q}\,q\,q^\dagger\,q\rangle_{\rho_N}$ and $\langle\overline{q}\,\lambda_a\,q\,q^\dagger\,\lambda_a\,q\rangle_{\rho_N}$, have odd chirality and vanish at zero density. For simplicity, these condensates are approximated by their factorized values.

The interpolating field χ^2_ν couples to both spin-1/2 and spin-3/2 states. The three vacuum sum rules obtained from the correlator $\Pi^{12}_{\mu\nu}(q)$ at $\rho_N = 0$ have been studied extensively in Refs. [15,16]. To obtain the finite-density sum rules from this mixed correlator, we follow the procedures established in Ref. [2–6]. The correlator $\Pi^{12}_{\mu\nu}(q)$ contains nine distinct structures at finite density. Here we only focus on the odd-chirality sum rules at the structures $\gamma_\mu\gamma_\nu$ and $\gamma_\mu \not{q} q_\nu$, which are

$$\lambda_1\,\lambda_2\,M_N^*\,e^{-(E_q^2-\mathbf{q}^2)/M^2} = -\frac{1}{8\pi^2}\,\langle\overline{q}q\rangle_{\rho_N}\,M^4\,E_1\,L^{8/27} + 2\,\overline{E}_q\,\langle\overline{q}q\rangle_{\rho_N}\langle q^\dagger q\rangle_{\rho_N}\,L^{8/27}$$
$$-\frac{1+3\beta}{96}\,\langle\overline{q}q\rangle_{\rho_N}\,\langle\frac{\alpha_s}{\pi}\,G^2\rangle_{\rho_N}\,L^{8/27}\,, \qquad (7)$$

and

$$\lambda_1\,\lambda_2\,\frac{1}{M_N^*}\,e^{-(E_q^2-\mathbf{q}^2)/M^2} = -\frac{1}{8\pi^2}\,\langle\overline{q}q\rangle_{\rho_N}\,M^2\,E_0\,L^{8/27} - \frac{3-\beta}{64\pi^2}\,\langle g_c\overline{q}\sigma\cdot Gq\rangle_{\rho_N}\,L^{-2/9}$$
$$+\frac{1+3\beta}{96}\,\langle\overline{q}q\rangle_{\rho_N}\,\langle\frac{\alpha_s}{\pi}\,G^2\rangle_{\rho_N}\,\frac{1}{M^2}\,L^{8/27}\,. \qquad (8)$$

Here λ_2 denotes the coupling of χ^2_ν to the quasi-nucleon state. The contributions of the even-chirality four-quark condensates to these two sum rules are multiplied by the current quark masses and are thus suppressed. In-medium factorization is adopted for the odd-chirality four-quark condensates. Here, dimension-five quark and quark-gluon condensates that vanish in vacuum are neglected as their contributions are numerically small [5]. The other sum rules obtained from the mixed correlator are either dependent on the even-chirality four-quark condensates or have vanishing Wilson coefficients for the majority of leading order OPE terms. (For example, the Wilson coefficients for the operators, $\overline{q}\gamma_\mu q$, $\overline{q}\gamma_\mu D_\nu q$, $\cdots$, $\overline{q}\gamma_\mu D_{\nu_1}\cdots D_{\nu_n} q$ vanish in this case.)

In sum rules (4), (5), (7), and (8), we have also included the dimension-seven condensate, $\langle\overline{q}q\rangle_{\rho_N}\,\langle\frac{\alpha_s}{\pi}\,G^2\rangle_{\rho_N}$, which was neglected in the previous studies. Inclusion of its contribution should make the valid regime in Borel mass larger and the predictions more reliable, as shown in the vacuum sum rules [16]. As the unfactorized dimension seven operators giving rise to $\langle\overline{q}q\rangle_{\rho_N}\,\langle\frac{\alpha_s}{\pi}\,G^2\rangle_{\rho_N}$ are chirally odd their density dependence should be qualitatively

similar to that of the quark condensate. This behavior arises naturally in the factorized form where the density dependence of the gluon condensate is estimated to be a 7% effect. There are many other dimension-seven operators; their contributions are assumed to be relatively small [16] and are neglected.

To analyze the sum rules, we follow the techniques introduced in Ref. [15] for determining the valid Borel region. We limit the continuum model contributions to 50% of the phenomenology, and maintain the contributions of the highest dimensional operators in the OPE to less than 10% of the sum of OPE terms. This defines a region in Borel mass M where a sum rule should be valid. If there is no region in which both conditions are satisfied, the sum rule is considered to be invalid and is discarded.

A comparison of (7) and (8) indicates that (7) will have a smaller region of validity than (8). The leading term of (7) is proportional to M^4 whereas (8) is proportional to M^2. The M^4 term has greater overlap with excited states and limiting continuum model contributions will restrict the upper Borel regime limit. In addition, a comparison of the magnitudes of the highest dimension operators in these sum rules indicates the lower limit will be larger for (7) when maintaining the promise of reasonable OPE convergence. It should not be surprising to find (7) to become invalid prior to (8) as density increases.

QCD sum rules relate the spectral parameters to the condensate values and other parameters. Any imprecise knowledge of these QCD inputs will give rise to uncertainties in the extracted spectral properties. Here we follow Ref. [16] and estimate these uncertainties via a Monte Carlo error analysis. Gaussian distributions for the condensate values and related parameters are generated via Monte Carlo. These distributions provide a distribution for the OPE and thus uncertainty estimates that are used in the χ^2 fit. In fitting the sum rules taken from the samples of condensate parameters, one learns how these uncertainties are mapped into uncertainties in the extracted spectral parameters.

As in previous works on finite-density sum rules, we use the linear density approximation for estimating the in-medium condensates:

$$\langle\widehat{O}\rangle_{\rho_N} = \langle\widehat{O}\rangle_{\rm vac} + \langle\widehat{O}\rangle_N \, \rho_N \ . \tag{9}$$

The values of vacuum condensates we use are [16] $a = -4\pi^2 \langle\overline{q}q\rangle_0 = 0.52 \pm 0.05$ GeV^3, $b = 4\pi^2 \langle(\alpha_s/\pi)G^2\rangle_0 = 1.2 \pm 0.6$ GeV^4, and $m_0^2 = -\langle g_c\overline{q}\sigma\cdot\mathcal{G}q\rangle_0/\langle\overline{q}q\rangle_0 = 0.72 \pm 0.08$ GeV^2. The quark mass m_q is chosen to satisfy the Gell-Mann–Oakes–Renner relation, $2\, m_q \, \langle\overline{q}q\rangle_0 = -m_\pi^2 \, f_\pi^2$. We adopt $\sigma_N = 0.045 \pm 0.007$ GeV [19], $\langle(\alpha_s/\pi)\, G^2\rangle_N = -0.65 \pm 0.10$ GeV, $\langle q^\dagger iD_0 q\rangle_N = 0.18 \pm 0.04$ GeV, $\langle g_c q^\dagger\sigma\cdot\mathcal{G}q\rangle_N = -0.1 \pm 0.5$ GeV^2, $\langle q^\dagger iD_0 iD_0 q\rangle_N + \frac{1}{12}\langle g_c q^\dagger\sigma\cdot\mathcal{G}q\rangle_N = 0.031 \pm 0.010$ GeV^2 [6]. Since the mixed condensate $\langle g_c\overline{q}\sigma \cdot Gq\rangle_{\rho_N}$ is chirally odd, we assume the same density dependence as for the quark condensate. We take $\mu = 0.5$ GeV and $\Lambda_{\rm QCD} = 150 \pm 40$ MeV and $\alpha_s/\pi = 0.0117 \pm 0.014$ at 1 GeV^2 [16]. To explore deviations from in-medium factorization of the chirally-even four-quark operators contributing to the last term of (5) we introduce a 100% standard error and consider $\kappa = 1.0 \pm 1.0$.

Before proceeding with the numerical analysis it is interesting to examine the density dependence of the new sum rules of (7) and (8). For both of these sum rules, the predominant density dependence is governed by the quark condensate. This density dependence is common to all terms of these OPEs. As such, the effects of increasing density will be to reduce the residue of the pole while the pole position remains largely unchanged. This result

should be robust, and is the key result absent in the former in-medium nucleon analysis. The approximate invariance of $M^* + \Sigma_v$ is manifest in (8) and is in accord with the expectations of phenomenology.

Our goal here is to evaluate the degree of consistency between the QCD sum rules and the expectations of relativistic mean-field phenomenology. The one firm conclusion from previous in-medium studies is that the vector self-energy is positive and a few hundred MeV. Hence, we begin by fixing $\Sigma_v = 0.25$ GeV at saturation density and searching for a region in which both sides of the QCD sum rules are valid [16]. These considerations eliminate the sum rules (4) and (7) from the following analysis as there is no valid Borel region as defined above. The implications of this result will be considered in a later work [20]. Thus we proceed with the sum rules (5) and (8) only.

The parameter β should be selected to minimize continuum model contributions while maintaining reasonable higher-dimension operator contributions such that the pole may be resolved from the continuum contributions [16,17]. The sum rule (5) indicates that these criteria cannot be satisfied simultaneously. We therefore select $\beta = -0.7$ for this sum rule to suppress the continuum contribution from the third term in the OPE. The continuum model contribution of the sum rule (8) is independent of β. We therefore simply set $\beta = 0$, as it is known that the second term of (2) has little overlap with the ground state nucleon [16,17].

Ideally, the sum rules of (5) and (8) would be optimized by a six parameter search of the two residues, two continuum thresholds and the scalar and vector self-energies. However, the final terms of (5) independent of the continuum model are small. A singular value decomposition of the covariance matrix reveals that these terms are not identified as a degree of freedom. Hence, to proceed, we have no choice but to equate the continuum thresholds of (5) and (8). In practice, this approximation is acceptable when the continuum model contributions are restricted as described above [16].

Fig. 1 displays the valid Borel regimes for the two sum rules (5) and (8). The corresponding fit for the central values of the QCD input parameters is illustrated in Fig. 2. The distributions for M^* and Σ_v are illustrated in Fig. 3. We find $M^* = 0.70^{+0.14}_{-0.10}$ GeV and $\Sigma_v = 0.32^{+0.07}_{-0.11}$ GeV at nuclear matter saturation density. Normalizing these results to the vacuum nucleon mass predicted by (8) provides our final result of $M^* = 0.64^{+0.13}_{-0.09}$ GeV and $\Sigma_v = 0.29^{+0.06}_{-0.10}$ GeV. These results are consistent with the expectations of relativistic phenomenology.

The density dependence of these results near saturation density appears to be weaker than previous analyses. Table I summarizes ratios of the finite density spectral parameters obtained from (5) and (8) at various densities. Median and standard errors from the median are reported as the distributions are not Gaussian. The trend of the ratios is in qualitative but not quantitative accord with the expectations of mean-field phenomenology. The uncertainties in the ratios for $M^* + \Sigma_v$ confirm that a determination of binding energies the order of 16 MeV is beyond present QCD sum rule analyses.

The analysis here has focused on two of the four sum rules which are insensitive to the even-chirality four-quark condensates and hold promise of providing reliable information on the density dependence of spectral parameters. Further examination of the sum rules is necessary to determine whether the sum rules which have been found to be invalid are at least consistent with the more reliable sum rules.

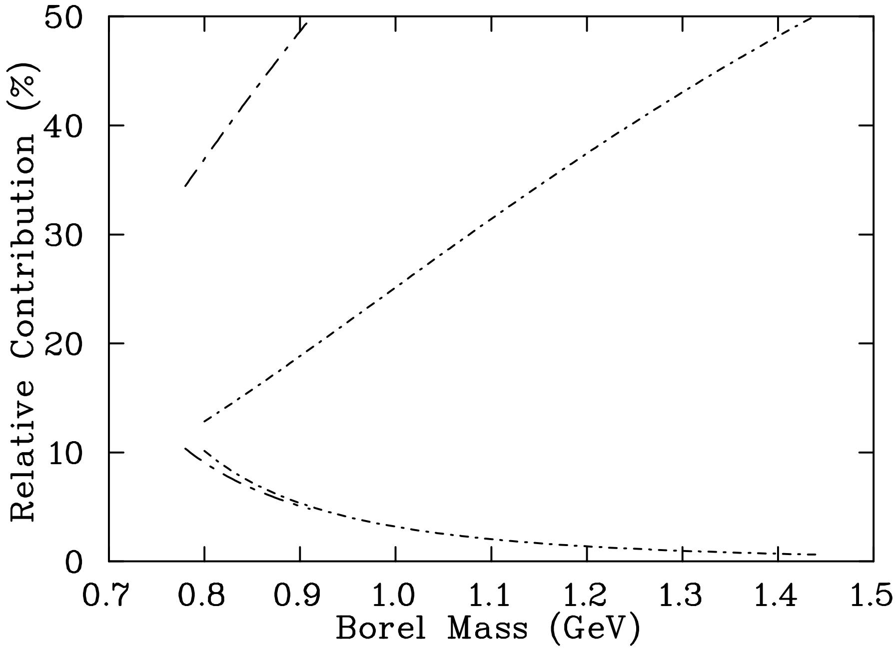

FIG. 1. Illustration of the valid Borel regimes for the sum rules of (5) (large dash) and (8) (fine dash). Both continuum model contributions (limited to 50% of the phenomenology) and highest dimension operator contributions (limited to 10% of the OPE) are illustrated.

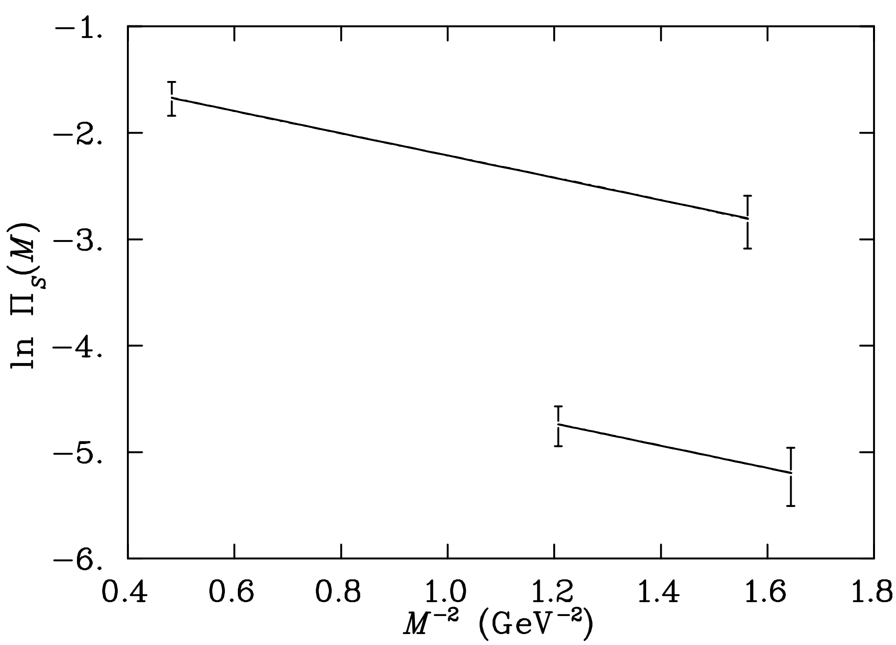

FIG. 2. The five parameter fit of the sum rules of (5) (large dash, lower) and (8) (fine dash, upper). The QCD−continuum (dashed) curves are hidden by the ground state (solid) curves in the near perfect fits. Only 2 of the 51 error bars used in the χ^2 fit are illustrated.

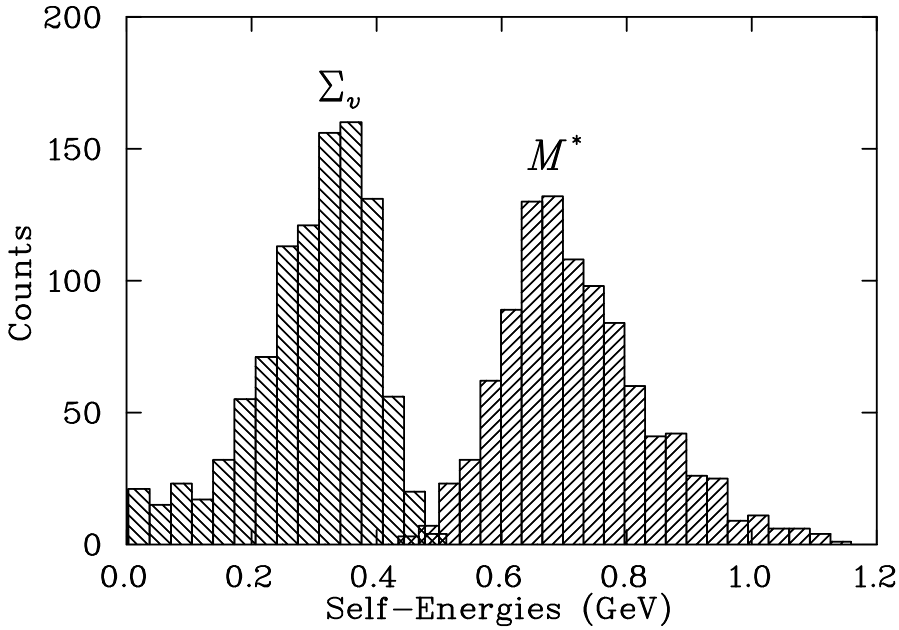

FIG. 3. Histogram for Σ_v and M^* obtained from a Monte Carlo sample of 1000 QCD parameters.

In summary, we have obtained two new QCD sum rules for nucleons in nuclear matter from a mixed correlator of spin-1/2 and spin-3/2 interpolating fields. These sum rules are insensitive to the large and poorly known even-chirality four-quark condensates and provide additional information on the nucleon scalar self-energy in nuclear matter. We analyzed these new sum rules, along with the sum rules obtained from spin-1/2 correlator. Uncertainties of the predictions due to imprecise knowledge of the condensate values and related parameters were obtained from a Monte Carlo error analysis. We found that the QCD sum-rule predictions for nucleon self-energies are consistent with the magnitudes but not the density dependence obtained in relativistic nuclear phenomenology.

TABLE I. Ratios of the finite density spectral parameters at various densities. Vacuum ratios report saturation-density / zero-density results as in Σ_v/M_N, M^*/M_N, $(M^*+\Sigma_v)/M_N$, w^*/w and $\lambda_1^*\lambda_2^*/\lambda_1\lambda_2$ while saturation density ratios report finite-density / saturation-density results.

Self-Energy	Vacuum Ratio	Saturation Ratios	
	$\rho_N = 1.0$	$\rho_N = 0.5$	$\rho_N = 1.5$
Σ_v	$0.30 \pm^{0.06}_{0.14}$	0.88 ± 0.09	1.09 ± 0.07
M^*	$0.69 \pm^{0.14}_{0.07}$	1.06 ± 0.05	0.96 ± 0.05
$M^* + \Sigma_v$	0.99 ± 0.03	1.00 ± 0.03	1.00 ± 0.04
w	1.01 ± 0.04	1.00 ± 0.03	1.00 ± 0.05
λ_1^2		0.55 ± 0.10	1.43 ± 0.29
$\lambda_1\lambda_2$	0.46 ± 0.08	1.35 ± 0.15	0.72 ± 0.12

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